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# THE MUZZLE FLASH OF GUNS AND ROCKETS: A TRANSLATION

Joseph M. Heimerl

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US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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This is a translation of a report that summarized the experimental work done in Germany up to about the year 1945 in the field of muzzle flash suppression. The experiments used real gun systems and employed a large number of different chemical additives as potential suppressants. Negative, as well as positive, results were reported. A brief discussion on rocket afterburning suppression and smoke attenuation was also given.

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## TRANSLATOR'S PREFACE

This is a translation of a report that summarizes the experimental work done in Germany up to about the year 1945 in the field of muzzle flash suppression. The experiments used real gun systems and employed a large number of different chemical additives as potential suppressants. Negative, as well as positive, results were reported. A brief discussion on the suppression of rocket afterburning and smoke attenuation was also presented.

The translation was undertaken with the goals of:

1. Providing the English reading scientific community with a document of some interest in the field of muzzle flash suppression; and

2. Allowing the author to become somewhat more familiar with the German technical language. Because of the latter goal I chose to be more literal than free with the translation, wherever possible.

Details for the most part are lacking and only general results or conclusions are cited in the original German text. Indeed there are four different references made; but, only one citation is presented in the standard format in common use today. The reference to Cranz is taken to be: Innere Ballistik by Dr. C. Cranz, Vol. 2, Section 23.2, 1926 (Julius Springer, Berlin). That of Lochte-Holtgreven is: "Die Temperatur des Muendungsfeuers bei der Pak 40," Report 10/43 from the Ballistisches Institut der Technischen Akademie der Luftwaffe, Berlin - Gatow dated 10 March 1943. The reference to Gallwitz was not found.

The symbols used in the text are defined as follows.

(...) = parenthetical remarks of the original text.

[...] = English words added as supplementary text, comment or explanation.

TN: = Translator's Note.

The units mentioned in the text are not SI. The following conversions can be used:

1 calorie = 4.184 joules, and

1 atmosphere = 0.101325 MPa.

This translation was begun in late 1984 as an after-hours exercise while the author was working at the Ballistic Research Laboratory, Aberdeen Proving Ground, MD. Like many such tasks it soon developed a life of its own. It was finished during the initial part of an exchange assignment at the Ernst Mach Institut, Abteilung fuer Ballistik, Weil-Lam-Rhein, Federal Republic of Germany.

G. Klingenberg (Ernst Mach Institut) and H. Mach (Institut Saint-Louis, France) generously gave of their time to read an earlier version of the translation. There is no doubt that their suggestions improved the accuracy

of the translation. However, I am solely responsible for any residual errors that may exist.

With the following text I believe that the first mentioned goal has been achieved and I can speak with some authority that the second goal has also been met.

J.M. Heimerl
Weil am Rhein
March 1985

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## I. ORIGIN AND TYPES OF MUZZLE FLASH

Very often with the shot from a firearm, fire appears at the muzzle. One can clearly distinguish two types:

a. Muzzle flash (Von Cranz labels it as "secondary muzzle flash").

b. Fire out of the muzzle.

This division results from the different origin and intensity of the light emission accompanying the shot and so brings about a different treatment with regard to attenuation.

Upon the firing of a shot the chemical processes in the combustion chamber and in the muzzle or gun barrel of the weapon are briefly and approximately outlined by the following: through the ignition of the shot powder there follows a change into gases which are mainly composed of $CO_2$, CO, $H_2$, water vapor and $N_2$. Depending on the different powder or gun types small quantities of NO, $CH_4$, heavy hydrocarbons, HCN and similar hydrogen-, nitrogen-, oxygen-, and carbon-compounds are then on hand as a result of cooling. Because of the high temperature of about 2000-3000K, these gas mixture components are already partially dissociated into free atoms O and H as well as into radicals, e.g., OH. During this process the mineral additives and impurities of the powder components, for example MgO, CaO, $Na_2O$ and the oxides of iron, contribute to the gas mixture in very small portions. Depending on the type of weapon, the ratio of caliber to gun barrel length, the energy content and construction of the powder type employed, its [the powder's] dimensioning and burning velocity as well as the gas pressure in the apparatus, the course of the chemical conversion in the gases may be directed so that for best use it [the chemical conversion] is completed before the exit of the projectile. [Sic.] With the expulsion of the powder gases, they now incur a pressure drop and are mixed with the outside air, with which a temperature drop is associated. In this instant one observes close to the muzzle a more or less intense visible emission that one has interpreted as the "after glow" [TN: primary muzzle flash] of the powder gases. It appears as a dark red glow (generally spherical with several short, claw type offshoots), that is soon, depending on the size of the apparatus, no longer visible at a small distance from the muzzle. [TN: Klingenberg has stated that the expansion fan is in fact a cone not a sphere and that the offshoots are due to the initial release of the exhaust gases into the low pressure of the precursor flow. The glow appeared spherical because the optical imaging resolution was not high enough.] In Germany this glow is denoted as "fire from the muzzle" [TN: primary muzzle flash]. Primary muzzle flash has little significance since it is hardly detected during daylight by the human eye without aid, and can only be detected in darkness. It will be quite generally overlooked by the enemy and many times it is not analyzable in his optical measuring apparatus.

With many weapons however this primary muzzle flash is masked by a second light emission. Because of the influx of oxygen from the air to the powder gases coming from the muzzle and through the mixing with the air, a combustible gas mixture is formed which ignites at some distance from the muzzle because of some heating. There occurs a type of explosive burning of the combustible portions contained in the gases associated with light

emission, that is denoted as [secondary] muzzle flash. Depending upon the size of the weapon, the light emission is more or less strong and bright, substantially larger in area and more irregular in shape than is the case with primary muzzle flash. Temporally the muzzle flash does not appear immediately after the shot, but there first elapses a small time till mixing and ignition has taken place. The muzzle flash can be easily made out by day and produces, owing to the named properties, one of the unpleasant side effects of the shot. One supposes that the ignition temperature is attained through the adiabatic compression of the gas mixture impacting on the atmospheric air. The intensity of each [secondary] "muzzle flash" masks the primary flash.

Whereas the primary flash is unavoidable and stays within tolerable limits, it consequently has found little interest for scientific investigations; as a result of the by far greater significance of the muzzle flash, a large sequence of tests have been done toward the explaining and influencing of this luminous phenomenon.

## II. FACTORS THAT CAUSE MUZZLE FLASH IN GUNS

The following elements are important in the behavior of muzzle flash.

### A. Factors that are Found in the Construction of Weapons

Besides the design of a weapon, i.e., the size of the caliber, the barrel length, the projectile weight and the muzzle pressure, the condition of the weapon should be mentioned. While the former exerts a "constant" effect on the muzzle flash, the effects of the barrel condition, i.e., wear of the grooves, erosion at the transition cone from combustion chamber to gun barrel, which involves: the extent of free flight of the projectile in the barrel, the type and material of the munition, and the projectile guidance, are strongly dependent on the lifetime of the barrels and therefore are not always of equal value for the appearance of muzzle flash. Even at equal gas pressure and equal performance worn gun tubes show muzzle flash more frequently than new barrels. Understandably enough barrels that are warm from shooting have an increased tendency toward muzzle flash, just as the level of $V_0$ [the projectile velocity] of an apparatus as well as the level of its gas pressure, particularly the muzzle gas pressure, increase the tendency. Generally it has been found that the tendency towards muzzle flash increases with the launch velocity of the projectile and decreases with performance.

Also significant is the type of munition, whether used as a cartridge or loose.

### B. Factors that are Caused by the Gun Powder

Naturally, of greater importance is the chemical composition of the propelling charge, which determines the energy content, the type and quantity of powder gases and its temperature. Powders with low caloric content and rich in nitrogen components can successfully influence muzzle flash. Furthermore the size of the weight of the powder load as well as the arrangement itself (thus the loading construction) are to be mentioned. Also the kind of powder types is important for muzzle flash. Thus the propellant charges made from pure nitrocellulose powder in the larger artillery pieces

tend more strongly to this light emission [muzzle flash] than the corresponding type containing nitroglycerine. It has often been observed that such powders shoot with and without muzzle flash apparently at random.

C. Factors that are Due to Atmospheric Conditions During Firing

In the first place the weather is to be mentioned. In the case of abnormally high atmospheric moisture, or fog, the muzzle flash occurs substantially more readily than in the case of dry weather. Also there was no success to detect a law governing the atmospheric influences (atmospheric humidity, atmospheric pressure, air temperature, etc.) from the occurrence or non-occurrence of the muzzle flash. Further the temperature of the powder is important; since powders stored in a warm place tend toward muzzle flash more strongly than those stored at correspondingly normal temperatures.

With these three larger groups one does not yet appear to have totally grasped all factors for the influence of muzzle flash. Namely the observations have been made in the case of artillery pieces that for the larger series of guns muzzle flash occurs again and again in irregular sequence and strength. The existing observations concerning the occurrence or disappearance of muzzle flash does not yet suffice for the statement of a "law," since the number of exceptions would be very large.

It is sufficiently well known, that the muzzle flash is a very undesirable side effect of gun firing, which through its intensity not only blinds but also reveals the gunner or the crew of a weapon. Of course muzzle flash is not of such importance for handguns and small caliber weapons as for the large caliber artillery pieces because of the size of the flash. Consequently the efforts to reduce or better to prevent entirely muzzle flash for these devices are of greater importance for engineering and tactics. The results and conclusions of the several investigations which were carried out in Germany in the past years for different large caliber weapons are reported here.

## III. INFLUENCING GUN MUZZLE FLASH

Of the above named three groups of factors, that affect muzzle flash in the case of an artillery piece, the element of weather generally is not controlled and so it can not be excluded [from the experiments]. Indeed it is a considerable challenge for a weapon to always be ready for a charge in any kind of weather.

The technical specifications for an artillery piece have thus far always been fixed according to the aspects of ballistic performance above all, then for the most part upon constructive changes, etc., arrangements for the decrease or prevention of muzzle flash were taken a little into consideration or entirely neglected. The tendency, to obtain the highest ballistic performance from a weapon, stands in opposition to the avoidance of muzzle flash.

Devices have been developed for gun barrels (cone-type barrel-pieces at the muzzle - a kind of small "cornet") that were to have blocked or delayed the mixing of the powder gases with the air so far as is possible, and in this

way prevent the formation of muzzle flash. [TN: Such conical devices cause a pre-expansion and reduce the shock strength resulting in a lower probability of muzzle flash.] The result was a reduced muzzle flash whose light was somewhat diminished. These contrivances have only been proved in the case of small caliber weapons, e.g., 2 cm, 3.7 cm, and 5 cm anti-aircraft machine guns and anti-tank guns. In the case of the larger artillery pieces these mechanical muzzle flash reduction devices could not be applied because of the higher muzzle pressures. [TN: Sic. The large amount of weight at the end of a long barrel would produce a very large moment arm.]

Entirely unsuitable is the proposal, to inject dry ice through an appropriate attachment into the powder gases at the muzzle immediately after the exit of the projectile from the barrel, in order to lower the temperature of the gases and moreover to stop the explosive burning through chemical passivity [TN: That is, the temperature is lowered by dilution with a cold inert gas]. The great technical expense to uniformly dispense against the muzzle pressure in the powder gases large quantities of dry ice or other chemicals by means of an appropriate apparatus within several milliseconds, would be justified -assuming success- only for a few valuable special apparatuses. For standard artillery such devices could by no means come into consideration because of logistic difficulties.

Thus of the known group of factors that influence muzzle flash, only the one concerning the propelling charge still remains. Up to now it has the best successes to report and also it alone in recent years has been pursued further and improved.

The most elementary influence on the muzzle flash by the powder can follow from an appropriate shaping of the powder grains, which indeed determines their own consumption. One must endeavor to complete the burning quickly before the projectile has left the barrel. In this way the powder gases exiting the muzzle already have a substantially lower temperature. Unfortunately this mode of action is not always feasible, because different ballistic demands of a cannon would not be able to be met regarding the projectile velocity and the gas pressure. Of the two useful dimensions for the powder grains naturally the more lively is always put in.

The most reliable and expedient method to influence muzzle flash is through the chemical composition of the powder. In this case one has the following possibilities:

a. the lowering of the energy content of a powder,

b. the insertion of muzzle flash suppression additives,

c. the insertion of powder components that produce inert gas products, specifically nitrogen, and,

d. the raising of the methane content in the powder gas, since methane-air-mixtures are especially hard to ignite.

As far as the interior ballistic performance of a cannon permit, all four ways have been tried.

The lowering of the energy content of the propelling charge for cannons from the 950 calorie-nitroglycerine based powder common some 30 years ago to the 700 calorie-diglycoldinitrate based powder common since 1937/38 brings, in addition to other improvements, an observable lowering of the temperature of the powder gases at the muzzle. Even though large fractions of the combustible substances exist in the powder-gas-air mixture, the temperature necessary for an ignition is less and less attainable, so that the explosive type burning is absent. In many cases this is attained through addition of appropriate muzzle flash suppressing substances with some good degree of safety. These "cold" powders need a charge weight extending up to 10% higher, so that it was difficult to get the charge into the chamber of older guns. For modern [TN: 1948] devices, especially in light of new developments, these requirements were met. For howitzers, mortars and similar weapons a change of propelling charge of that kind was not possible since the ballistic demands of such a gun type could not be met with a 700 calorie powder. For these weapons one could only tamp the muzzle flash suppressor closer, when the nitroguanidine powder, developed in the years 1938-40, was introduced. By reason of the favorable property of this powder type, the energy content of the propelling charge for howitzers and mortars could be lowered from 1250 to 925 calories. Since such a nitroguanidine powder is rich in nitrogen, the risk that the powder-gas-air mixture would ignite as muzzle flash after the shot was substantially lessened. The nitrogen content, calculated from the composition of the powder, for the most common howitzer powder are:

| Flake-Powder | Calories | $\%N_2$ |
|---|---|---|
| Nitroglycerine | 1250 | 15 |
| Diglycoldinitrate | 1020 | 13.3 |
| Nitroguanidine | 925 | 25.3 |

Through the use of the nitroguanidine powder, first a reduction of the muzzle flash [without the use of additives] was reached in the case of howitzers and mortars; of course a small amount of muzzle flash suppression additives (0.25 up to 1.5% depending on the caliber and loading) would have to be added to the powder, in order to lower the light intensity with some measure of certainty. (Diglycol powder with the same energy content would necessitate a substantially larger amount of muzzle flash suppression additive.)

The result with nitroguanidine powder was more effective in the case of cannons with small to average caliber, where indeed the energy content of the propelling charge can be reduced to about 700 calories. Modern guns, (e.g., the larger anti-aircraft, anti-tank and armored car weapons) have been equipped with that kind of nitroguanidine, that is weapons that have a rapid fire as well as a high projectile velocity. In the case of guns with very large caliber of course no muzzle flash suppression was attained from these methods. Thus for modern powder types the muzzle flash is nearly suppressed, even if the powder gas composition at the muzzle still exhibits predominantly combustible parts. On the basis of gas analysis from powder gas probes of a 10 cm cannon, of course carried out with howitzer powder for the case of less than full performance, the decomposition equations show the ratio of the still unburned part ($CO+H_2+CH_4$) to the burned or uncombustible parts ($CO_2+H_2O+N_2$) in the chamber and at the muzzle:

| POWDER | ENERGY | CHAMBER | MUZZLE |
|---|---|---|---|
| Nitroglycerine | 1250 cal | 0.65 | 0.62 |
| Nitroguanidine | 925 cal | 1.15 | 1.07 |

Thus it is less the predominance of uncombustible or previously burned parts in the powdergas that prevents the explosive type combustion after the shot; but rather it is the temperature that is limited through these types of combustion products.

By the introduction of the 700 calorie powder, position a of the above mentioned four possibilities, to suppress the muzzle flash by means of chemical [TN:read instead: thermodynamical] effects, has been fairly exhausted. A further decrease of the energy content of the propelling charge would not be suitable since usually the ballistic difficulties and the increased smoke formation outweigh the benefits. The nitroguanidine powder is an example of the above mentioned position c. Very likely still other substances with large nitrogen content favorable for a muzzle flash suppressor can possibly be employed.

In the case of the above mentioned types of propelling charges, according to prevailing practices, always a more or less small part of muzzle flash suppression additives -see position b- is used up, which additives completely suppress the appearance of the light emission. They will be able to be [added in] considerably smaller [amounts] than those in the case of the normal powder types with over 800 calories. The knowledge of the effect of these certain chemicals is already very old, but no one could state anything about the causes and the chemistry. Already in the time of the first world war (1914-1918) extensive test firing with very odd chemical compositions have been systematically and randomly carried out. The results, found purely empirically, taught that by far the most successful suppression of muzzle flash is obtained from one small series of potassium salts. It is possible, but hardly expected that the other chemicals that were ineffective [in the old tests] in cannons with 950 or 820 calorie-powder or in howitzers with 1250 calorie-powder would be more successful in the case of cold or nitroguanidine powder propelling charges. The potassium salts show a different suppression strength as a function of the energy content of the powder, which [strength] is the best in the case of the types mentioned first of all [below]. Ranked according to their effectiveness is the series of potassium salts:

| | |
|---|---|
| $K_2SO_4$ | potassium sulfate |
| $KNO_3$ | potassium nitrate |
| $KHC_4H_4O_6$ | potassium bitartrate |
| $KCl$ | potassium chloride (in Germany also frequently known as "Dueneberger's Salt") |

$K_2SO_4$ and $KNO_3$ have proved to be the most successful of these substances. It could be established that in mixing them with the cold powder the suppressing of the muzzle flash takes place fairly regularly in most gun types and thereby is more or less sufficient. The content of $K_2SO_4$ or $KNO_3$ must be developed by gun firings separately for each gun caliber and for each propelling charge type. Generally for the cold powder the portion for cannons amounts to 0.5 to 3% -exceptions: for the larger calibers to 5%, and for

howitzer powder 0.25 to 1.5%. The salt is included either in with the powder at the time of manufacture, or else, as in the last year of the second world war, inserted in cartridge bags or in the form of disks of powder -with a content of 50 to 60% salt in powder- as a flash hider wad added in front of the propelling charge. A difference in the effect on the suppressing in these different arrangements could hardly be determined. For muzzle flash that is difficult to reduce, a dose over 5% $K_2SO_4$ is not advisable, since with employment of excessively large amounts the undesirable attendant glow of light changes into the form of an intolerable smoke. (See below for details.) The case for $KNO_3$ in the guns is hardly less than the $K_2SO_4$ in its effect; it has been used with cold powders in cannon propelling charges in amounts up to 4%. The oxygen content of the salt which brings about a slight elevation in the energy content of the powder is disadvantageous. Thus, while one saves a small quantity of calorie-lowering substances through the incorporation of $K_2SO_4$ in the propelling charge, this is not the case with the using of $KNO_3$.

The $KHC_4H_4O_6$ had proved to be good as a muzzle flash suppressant additive. In Germany potassium bitartrate simply did not find the wide spread use as the other two potassium salts, at first because of difficulties in the raw materials situation and then this substance reacts somewhat acidically so that the chemical stability can be detrimentally affected in the case of larger portions in the powder. The suppressing of the muzzle flash by means of $KHC_4H_4O_6$ is not quite as good and not always so gratifying as in the case of the sulfate or the nitrate; also the noticeably increased appearance of smoke is undesirable.

In Germany KCl [had] been common in the years up to 1918 but then became displaced by the other known potassium salts.

Because of the raw materials situation in Germany other alkali salts, as for example phosphates, have not been sufficiently tested enough. Potassium metaphosphate ($KPO_3$), which is calculated as the most potassium rich salt, has frequently been tested. Thereby one established that the muzzle flash suppressing action is very slight. Attempts with potassium [substituted] humic acid have not brought any clear results.

The possibility according to the above mentioned position d, to evolve relatively more hydrocarbons, for example methane, through special additives in the gun powder during combustion and thereby to suppress the muzzle flash, has not reached any importance. As attempts with carbon-rich substances, e.g., aluminum carbide ($Al_4C_3$), showed, a reduction of the light emission did not occur during shooting. Thus it appears not to be the case, as one could assume in analogy to similar processes, that the hard-to-ignite methane-air mixtures also exert a substantive influence on the process in and in front of the gun tube. Simply the methane balance in the powder gas can be distorted by the added amounts of methane, through which a lowering of the combustion temperature is caused.

Up till now, one has made many statements about the nature and method how these chemicals join in inhibiting the formation of a muzzle flash. One has to consider as open whether they always prove completely correct since, indeed, as has already been brought out above, the muzzle flash depends on many factors and up to now there is no known "law" concerning the origin or non-origin of this light emission. In most cases the investigations were

carried out for one gun system, then the arguments for the explanation of the muzzle flash no longer need to be correct for other weapons.

According to modern [TN:1948] views, the combustion of the powder in the gun tube or the explosive type conversion of the gas after mixing with the air at a certain distance in front of the muzzle proceeds in a chain reaction. These chain branching reactions are very energetic, so that they can be associated with light emission. With the presence of certain substances -in this case the alkali salts- a premature interruption of the conversion through chain-breaking reactions can take place. The reaction energy is removed through triple impacts by participating reactants [TN: three-body reactions] or through the influence of walls, thus solid substances [TN:particles].

The former possibility would be the more realizable at a high pressure. Through this perhaps one could explain the known phenomenon, that weapons that are fully loaded, hence of greater performance, shoot free of muzzle flash; but on the contrary, in the case of partial loading -in order to solve other artillery problems- [weapons] again shoot with muzzle flash because of the reduced gas pressure or, in other words, because of the smaller burning velocity of the powder.

The second named possibility, to mitigate the course of the chain reactions through wall reactions, could occur in the case of muzzle flash suppression by means of alkali salts, in which the latter alone through its presence as a solid substance so strongly breaks the reaction sequence of the the powder gas-air-mixture combustion, that the resulting temperature is not sufficient for a luminous emission. Lochte-Holtgreven could determine with the aid of spectroscopically ascertained temperature measurements of the muzzle flash, for example, [that] a lowering of the temperature in front of the muzzle is produced through the presence of $K_2SO_4$ in the powder.

Investigations in Russia concerning muzzle flash lead to similar conclusions. Thus, next to the breaking of the reaction chain, the recombination of OH radicals in the powder-gas-air mixture should also bring about a break-down of the reaction [chain].

Even if the appearance or disappearance of the muzzle flash should have been correctly interpreted through these explanations, there still remains to clear up the question, why according to existing observations only the potassium [TN: read instead "alkali"] salts cause a suppressing of the muzzle flash in the preponderance of the measurements. For the clarification of this problem the greater series of tests have been accomplished in Germany in the Dueneberg factory in cooperation with the office of Army weapons; these tests are performed according to different working hypotheses. Generally only such substances were selected that could have been tried first by reason of their chemically neutral behavior in the powder-gel -without therefore abandoning the chemical stability of the nitric acid ester- and then also had to have at one's disposal an adequate measure of reasonably priced raw materials for the larger charges. But one could very soon depart from the former above mentioned principal, since one added the chemicals in the cartridge bag as a flash-hider wad to the propelling charge. Also rarer substances had been tested, which as "academic" experiments were to have contributed to the proof of the working hypothesis. The ballistic attraction of these powder probes or

propelling charges took place partly in the 10 cm-howitzer or 10 cm-cannon, also partly in the 8.8 cm anti-aircraft 18.

In most cases the firing by day brought about a decision whether the substance affected a suppression, in the critical cases of course a night firing would be carried out.

In the first series of experiments salts had been tested, in which cases the potassium cation first of all had been replaced by its neighbors in the periodic system: lithium, sodium, rubidium, cesium, calcium, and barium. It was shown that the alkali metals lithium, rubidium, and cesium caused a reduction of the muzzle flash, which did not achieve by far [the level of reduction] of the above mentioned potassium salts. Among these salts very little difference could be observed; it appears as if a slightly stronger reduction in the muzzle flash follows increasing atomic weight according to the periodic system. Of the sodium salts the best proved to be the bicarbonate ($NaHCO_3$) and the oxalate ($Na_2C_2O_4$). The latter has also found use with known limitations as muzzle flash suppression additive for standard propelling charges especially in the case of the navy. Generally it could be determined that the type of anion of the alkali salt for muzzle flash [suppression] does not have the same importance as the cation. (Of course differences are clearly able to be established.) One also has tested the pure alkali metals sodium and potassium themselves -they were placed in the cartridge under petroleum in appropriate glass vessels of powdered charge- and thereby one determined, that only the potassium caused a suppression of the muzzle flash. [TN: Chemically this is difficult to understand. It has been suggested by Mach that insufficient amounts of sodium had been vaporized relative to the potassium.]

In a second series of tests substances were sought that were distinguished by a larger heat of dissociation. One presumed that an influence of the muzzle flash is attained directly through this property which is very important in the case of the potassium salts, because the heat loss owing to the thermal decomposition produces a cooling down of the powder gas-air-mixture below the ignition point. In portions from one to three per cent the following have been tested in large guns:

| | |
|---|---|
| Potassium-silicone-fluoride | $K_2SiF_6$ |
| Potassium phosphate | $K_3PO_4$ |
| Calcium phosphate | $Ca(PO_4)_2$ |
| Barium phosphate | $Ba_3(PO_4)_2$ |
| Borax | $Na_2B_4O_7 \cdot 10H_2O$ |
| Apatit | $Ca_5(PO_4)_3(Cl,F)$ |
| Calcium fluoride | $CaF_2$ |
| Titanium oxide | $TiO_2$. |

Hardly anything was observed of a reduction of the muzzle flash, only those chemicals that contain potassium produced a reduction of the light emission during shooting.

In a broader series of experiments soaps had been investigated for muzzle flash reduction, which soaps were often named as successful additives in the literature or in patent documents. Of course these chemical compounds could be utilized only in a limited way, since they operate on the basis of their alkalinity, decomposing into the powder components and in addition, they make the setting of the powder gel almost impossible owing to their lubricating action. Of course this difficulty could have been avoided in this way: one could include these additives of the propelling charge as flash-reducer wads in paper cups or the like. In percentages from 0.5 to 1.5% the following had been tested:

| | |
|---|---|
| Potassium Palemate | $KC_{16}H_{31}O_2$ |
| Calcium Octadeceneoate | $Ca(C_{18}H_{33}O_2)_2$ |
| Sodium Octadeceneoate | $Na(C_{18}H_{33}O_2)$ |
| Butyl Octadecanoate | $C_4H_9(C_{18}H_{35}O_2)$ |
| Stearatic acid | $CH_3(CH_2)_{16}COOH$ |
| Oleic acid | $CH_3(CH_2)_7CH{:}CH(OH_2)_7COOH$ |
| Palmitic acid | $CH_3(CH_2)_{14} \cdot COOH$ |

The results of these attempts to probe the shots were not satisfactory. A reduction was not observed, again only the potassium containing substances showed a little more positive results. Of course they did not reach that level [of suppression] of the organic alkali salts.

In the fourth series of experiments the working hypothesis, analogous to the methods in the case of some chemical synthesis, was followed: burnings of gas mixtures through catalysts to control their course, generally in mixtures of metal and metal oxide (ratio 1:1). Thus one also hoped to control the burnable powder-gas-air mixture in front of the gun muzzle by means of the presence of such compounds so that the otherwise explosive type transition outside of the gun tube would terminate without light emission; therefore, in the case of relatively lower temperature would perhaps terminate inside of the gun tube. There were ballistically tested in concentrations of 1 and 2% in the powder loading:

| | |
|---|---|
| Iron/iron-oxide | $Fe/Fe_2O_3$ |
| Molybdenum/molybdenum-oxide | $Mo/MoO_3$ |
| Copper/copper-oxide | $Cu/CuO$ |
| Magnesium/magnesium-oxide | $Mg/MgO$. |

All shots exhibited obvious muzzle flash. There were now such mixes or substances tested, which are known as catalyst-poisons in the chemical reaction kinetics. One hoped to directly prevent the start of the transition through material of that kind. In similar manner as above there were investigated:

| | |
|---|---|
| Arsenic/arsenic-trioxide | $As/As_2O_3$ |
| Arsenic/arsenic sulfide | $As/AsS$ |
| Potassium cyanide | KCN. |

Only the last substance of these three tests showed some reduction of the muzzle flash. But it did not bring any proof for the working hypothesis, since the suppression can also be explained by means of the known property of the potassium salt. In one other series of experiments, substances were tested that in the case of the combustion motors inhibited early ignition of the gas mixture (motor "knock"). The metal-organic compounds:

| | |
|---|---|
| Tetraethyl lead | $Pb(C_2H_5)_4$, |
| Iron carbonyl | $Fe(CO)_5$, and |
| Nickel carbonyl | $Ni(CO)_5$ |

were ballistically tested. Results were negative. Finally in a series of experiments, substances were investigated for muzzle flash suppression that are known as good absorbers for gases, with similar negative results. They ought to have brought about a kind of unfavorable distribution of the combustible parts owing to their porosity in the powder-gas-air mixture, so that an explosive type transition can not set in or is reduced. Tested were:

Asbestos powder,
Cupric acid in gel form,
Tonsil, and
Active charcoal.

With these tests, the experiments to find an explanation concerning the mode of operation of the potassium salt or concerning other methods of attack on muzzle flash suppression were given up. The firings have not brought any unequivocal result whatsoever. The point of view illustrated at the beginning, concerning muzzle flash suppression by means of the chain breaking reaction in the solid phase, was not completely confirmed through the results of the just named series of experiments, since indeed it appears to occur only for alkali salts with high atomic weight of the cation. Noteworthy is the observation that metallic potassium itself also influenced the muzzle flash. One has to explain this through the wall reaction in which one assumes, that during the combustion in the cannon a transition has taken place to a potassium salt, e.g., potassium carbonate or potassium oxide. Still for each case a specific property of the potassium, rubidium and cesium has to be of greater importance for the muzzle flash suppression. One has already supposed seeing this in the electronic structure of the atoms.

It is noteworthy that in the case of the use of the alkali salts in the reduced muzzle flash, a strong flame coloration is not detected but rather only a quite weak one or not at all; and, in the case of the spectroscopic investigation the spectral lines are not detected in the proportion as one should have expected. So it appears, that the salt has already undergone a change in the gun tube in the case of powder combustion, and that free atoms or ions no longer arrive at the zone of the muzzle flash. [TN: Klingenberg has suggested that the limited optical resolution of the spectroscopes available and the high continuum radiation probably caused this interpretation.] Perhaps association to the metal atom with a kind of strong binding follows in the case of the chain branching reaction, that a distortion of the electron cloud occurs, through which it has lost its ready ability to emit light as a free atom. [Sic.] Following the latest reflections of Hinshelwood (Proc. Roy. Soc., Vol. A188, p. 9, Dec 1946) the muzzle flash reduction by means of alkali salt is due to the fact that the combining of

hydrogen and oxygen in the combustion zone is reduced to about 100-fold and more of the rate of combustion. One presumes to have found a reaction mechanism therein that a recombination over to the alkali hydride takes place owing to the presence of the salt additives and thereby an interception of the hydrogen atom takes place that is important for the reaction decline.

Now how far other metals also catalytically influence the transition of the powder gas at the gun muzzle, might not have been adequately enough investigated through the above mentioned series of experiments with the metal/metal-oxide mixtures or with the catalyst-series.

## IV. THE MUZZLE FLASH FROM ROCKETS

With the switch of the propelling charges from black powder to the smokeless POL-powder [TN: powder without solvent intermediate], in the years 1937-1938, the problem of after-burning suppression for the rockets was not of great importance. One was already very satisfied that the otherwise usual smoke trail would be significantly diminished through the use of modern types of powders because of their substantially smaller particle content. In the course of the many-sided development of the rocket powder a suppression of the after-burning would also be desired from tactical considerations. This task is more difficult to solve than the suppression of muzzle flash in the case of guns, since indeed the nozzles of rockets are very short in contrast to gun tubes or gun barrels. Because of the significantly longer burntime of the rocket propelling charge these light emissions are of greater duration. For these reasons it appears questionable whether a satisfactory suppression of the flash for the rockets can be attained.

That this effect can still be attained in the case of rockets must thus be addressed from a theoretical stand point. In contrast to the guns the pressure in the combustion chamber of the rockets is considerably less (2000 to 3000 atm vs. 100 to 250 atm). The powder gases streaming out of the nozzle do not produce so strong an adiabatic compression in the outside air as is observed at the gun tube muzzle. If one chooses the inner pressure of the rocket to be very low and then provides for a uniform expansion through a suitable form of nozzle, whereby a cooling down of the powder gas is also accomplished in addition to a lowering of the pressure, then the tendency towards muzzle flash is smaller. Purely for construction reasons one could not always employ this possibility of flash reduction in practice; that is through choice of suitable nozzle and of low inner pressure.

So far as was known, experiments for the attenuating of the afterburning have been carried out only considering a chemical influence of the propelling charge. A lowering of the caloric content is not applicable for these goals in the case of the rockets, otherwise the ballistic requirements are not able to be met. In Germany one has more precisely tested only a suppressant containing the potassium salt additives tried with guns and has found that a content of 1 to 3% potassium nitrate suffices for a few standard propelling charges. Greater amounts would have disagreeably intensified the smoke trail of the rockets.

Still the finding by Lochte-Holtgreven during his spectroscopic temperature measurements in the luminous exhaust of rockets should be

mentioned. This is analogous to the finding in the gun experiments in which potassium salt additives cause a displacement of the [maximum] temperature in the direction of the combustion chamber.

Rockets without afterburning are realizable in which previously vaporizable substances are utilized as propellant. Their functioning depends upon this: these chemicals, after they have been brought to a fixed temperature through a type of ignition, give off gases in sufficient quantity. This condition is maintained by means of the decomposition heating that occurs. The process follows without the appearance of afterburning. The practical significance of such afterburning-free rockets has still not been acknowledged. In an overview of rocket-powder development of past decades it is to be noted that the luminous appearances at the nozzle are undesirable to be sure, but they have not by far assumed such importance as the muzzle flash associated with shooting from guns. Many other more pressing problems stood in the foreground, so that one was satisfied even with only an attenuation of the afterburning.

## V. SMOKE AND MUZZLE FLASH SUPPRESSION

As previously mentioned above, in the case of all successful experiments to suppress muzzle flash in guns or rockets there appears one other undesirable accompanying phenomenon in the form of smoke. For a weapon the stronger the muzzle flash is, and thereby requiring a large portion of additives for muzzle flash reduction, then the more smoke is produced. Gallwitz previously spoke of this observation as a type of law of nature. Moreover, following Gallwitz there could be no compromise. For instance, if the required percentage of muzzle flash suppression additive is somewhat reduced then there by no means appears a small muzzle flash with little smoke, but rather there appears either muzzle flash at full strength or smoke. There is no other choice. Earlier the smoke at the gun muzzle was at first taken as the lesser evil in the bargain; in the last years of the war however it became more and more urgent to more strongly abate this accompanying phenomenon of the shot, too.

This task could be attained but only by an essential change in the chemical composition of the propelling charge. Among the powder-smoke at the gun muzzle one has to understand a colloidal system of the smallest solid and liquid particles in air. The small particles are: first, the mineral constituents in the powder, as well as those constituents that remain in the considerable base and auxiliary materials that are present as carbon, only still unburnt; and, further those droplets of water vapor that condensed in front of the gun during the expansion of the powder gases and during the thorough mixing with the air. Finally there belongs in addition the different chemical compounds through the condensation that follows the cooling, e.g., ammoniumcarbonate or ammoniumcarbonamine. The color, quantity and density of the smoke is naturally dependent on the type of projectile as well as the amount and composition of the propelling charge. Generally the powder-smoke appears in front of the gun muzzle as a bright to dark-gray cloud that is distorted within a short time. Its density and residence is very dependent on the weather during which it is shot. The smoke occurs especially strong in the case of the propelling charge with the 700 calorie powder type, which indeed undergoes an incomplete condensation partly in the smoke, e.g.,

ammoniumcarbonate, and traces of hydrocyanic acid, are suspended with or in the water vapor droplets. The smoke from gun powder of this type frequently appears bright gray and at first is very thick so that the view through it is almost impossible. It then lies to some extent as a heavy fog for 10 to 30 seconds in front of the gun muzzle. In damp weather this characteristic especially makes itself disagreeably noticeable. Machine weapons and guns with rapid series shots are many times strongly hindered in their operation by means of this powder smoke, since under certain conditions the gun crew could no longer make out the enemy.

For these reasons it was unconditionally necessary to strive for an abatement of the quantity and density of smoke in the vicinity of the shot. The fastest and simplest way appeared to be a change in the composition of the propelling charge. Deliberations showed correctly that most probably such components are chosen on the ground of theoretically accepted conversion of a powder into gases, which components could form little carbon, water and ammonia. In this sense there were found as appropriate:

| | | |
|---|---|---|
| | | $N{=}CH_2$ |
| Methylene urea | O=C | |
| | | $NH_2$ |
| | | NHCN |
| Dicyanogendiamine | HN=C | |
| | | $NH_2$ |

which were used in the powder composition in proportions from 15 to 20%. Such powder was fired particularly in motor car guns, armor and attack guns with high fire and shot performance. Even during unfavorable weather the smoke from this type was very bright, thin, transparent and easily dissolved. Naturally such powder compositions once more showed very slight muzzle flash. The usual practical method, to obtain a suppressant by means of potassium sulfate, had success to be sure, but again it brought a slight increase in smoke. Thus one looked for other muzzle flash suppressant additives and found thereby that oxalic acid ($H_2C_2O_4$) and its alkali salts, especially potassium acid oxalate ($KHC_2O_4$) and sodium oxalate ($Na_2C_2O_4$) brought good results. The first two substances, owing to their chemical behavior (acid reaction with pH ca. 2-4), could be added to the propellant charges only in the shape of a flash reducing wad which had to be particularly dust proof. Also, wads with nitroguanidine stood the test exceptionally well. In Germany in the last years one turned more and more to use potassium tetraoxalate and nitroguanidine for new developments as a muzzle flash reducer, as long as reasonably priced raw materials could somehow be produced.

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